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Abstract

A debt-based economy requires the accumulation of more and more debt to finance economic growth, while future economic growth is needed to repay the debt. And so the cycle continues. Despite global debt reaching unprecedented levels, little research has been done to understand the impacts of debt dynamics on environmental sustainability. Here we explore the environmental impacts of the debt-growth cycle in Indonesia, the world's largest debt-based producer of palm oil. Our empirical Agent-Based Model analyses the future effects (2018-2050) of power (im)balance scenarios between debt-driven economic forces (i.e. banks, firms), and conservation forces, on two ecosystem services (food production, climate regulation) and biodiversity. The model shows the trade-offs and synergies among these indicators for Business As Usual as compared to alternative scenarios. Results show that debt-driven economic forces can partially support environmental conservation, provided the state's role in protecting the environment is reinforced. Our analysis provides a lesson for developing countries that are highly dependent on debt-based production systems: sustainable development pathways can be achievable in the short- and medium-terms; however, reaching long-term sustainability requires reduced dependency on external financial powers, as well as further government intervention to protect the environment from the rough edges of the market economy.

Keywords: *sustainable development; social-ecological system; debt; palm oil; ecosystem services; agent-based model.*

1. Introduction

The current standard approach of a debt-based economy may seriously threaten both economic development and environmental sustainability (ICSU and ISSC, 2015). Economic growth requires the accumulation of more and more debt, while future growth – fuelled by ever-increasing amounts of energy and resources – is needed to repay the debt (Daly, 2011). Although decoupling economic growth from environmental pressures is at the heart of initiatives such as the Green Economy Initiative of UNEP, frameworks for achieving this goal are still in their infancy (UNEP, 2011). Thus, there is a need to advance the current fragmented and circumstantial evidence of the relationship between debt dynamics and environmental sustainability.

The debt-(un)sustainability relationship is highly noticeable in Southeast Asia, where more than $45 billion (2010-2017) in credits have been lent by overseas banks to companies operating in different natural resource sectors (e.g. palm oil, timber, pulp and paper) (Forest & Finance, 2016). The palm oil industry in Indonesia is particularly important, having borrowed more credit facilities than any other sector in the country to fund palm oil production (i.e. USD 9.4 billion), more than any other palm oil industry in Southeast Asia (Forest & Finance, 2016).

Analysing the relationship between debt and environmental sustainability in Indonesia is important because this country is a focal point for key trade-offs between climate change mitigation, biodiversity conservation and food production. First, Indonesia is one of the world's top five Green House Gas (GHG) emitting countries; this is the main reason why Indonesia has set a goal to reduce its GHG emissions by 26% by 2020 (Paltseva *et al*., 2016). Second, tropical forests in Southeast Asia overlap with four of the world's distinct "biodiversity hotspots", with Indonesia having the highest plant species richness in the world (ICCT, 2016). Finally, Indonesia is the world's biggest producer of crude palm oil (CPO), and in 2015 set the goal of nearly doubling the area for oil palm cultivation by 2020 (UNDP, 2015).

The Government of Indonesia is facing opposing and conflicting goals for 2020 and beyond – to reduce GHG emissions, halt biodiversity loss and boost food production (Republic of Indonesia, 2016). Can these goals be achieved in Indonesia under a debt-based palm oil industry and economy? The Agent-Based Model (ABM) presented here examines this question by modelling the effects on social-ecological system (SES) (un)sustainability of power (im)balance scenarios between debt-driven economic forces (i.e. banks and firms) and conservation forces (i.e. governments and public institutions). The SES model shows the impact of different future scenarios (2018-2050) on CO_2 emissions, biodiversity loss and CPO production in Indonesia, and analyses impacts on economic and environmental indicators. The short and medium-term governance and policy implications for SES sustainability in Indonesia are discussed, together with potential long-term 'system rigidity' effects enhanced by power inequalities among economic and conservation forces.

2. Materials and Methods

2.1. Study area and problem formulation

The study site (Figure 1) comprises the provinces of Kalimantan (743,330km^2), Sumatra (473,481 km^2) and Papua (319,036km^2), making a total of 1,525,847km^2. These three provinces cover 80% of the total land area in Indonesia and are some of the main producers and exporters of palm oil world-wide. Indonesian annual CPO production, which is expected to double by 2020 (UNDP, 2015), is financially supported by some of the largest commercial banks headquartered in the U.S. (e.g. Bank of America), Europe (e.g. Credit Suisse) and China (e.g. Industrial and Commercial Bank of China), among others. The palm oil industry in Indonesia received USD 9.4 million in credits between 2010 and 2017 (Forest and Finance, 2016) to cover the upfront costs of producing CPO, i.e. for developing land, planting seedlings and building infrastructure (Chain Reaction Research, 2017). Such reliance on external funding by the palm oil industry encourages a continuous debt-driven CPO production process which, together with logging, mineral extraction and forest fires, threatens biodiversity and releases significant quantities of carbon into the atmosphere (Carlson *et al*., 2013). These environmental impacts are particularly important in Indonesia, considered to be one of the major evolutionary hotspots of biodiversity in Southeast Asia (de Bruyn *et al*., 2014); and where the aboveground biomass carrying capacity of some parts (essential for climate change mitigation) is 60% higher than in Amazonia forests (Slik *et al*., 2010).

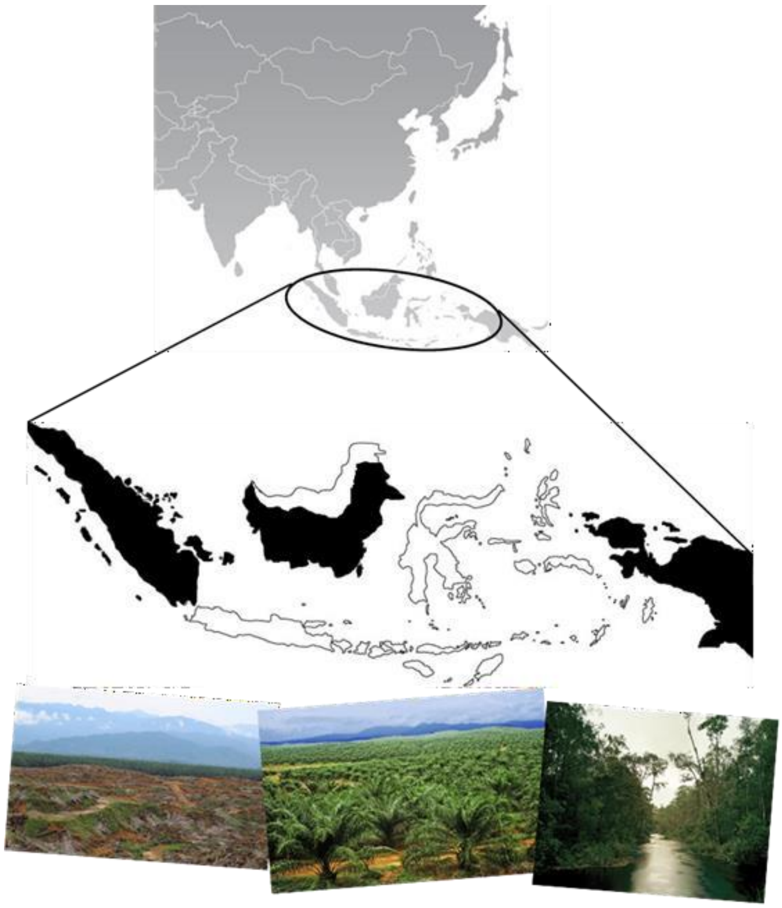


Figure 1: **Geographic location of the case-study area**. Indonesia (top map) and the social-ecological system modelled representing the provinces of Sumatra, Kalimantan and Papua (in black, bottom map). Photographs on the bottom show national examples of degraded land (left), oil palm plantations (centre), and protected primary swamp forest (right).

Although various streams of ecological economics offer a biophysical view of the economy, a sound understanding of how key macroeconomic issues, e.g. global debt dynamics, are entangled with environmental shifts and destructive feedbacks at lower levels is missing (Klitgaard and Krall, 2012). The model presented here addresses this research gap while contributing to identifying how the 2020 (and further) objective of Indonesia to reduce GHG emissions, halt biodiversity loss and boost production of agricultural commodities can be achieved (Republic of Indonesia, 2016). For this purpose, four different future scenarios are modelled for the period 2018-2050: Business As Usual (BAU); Reduce Biodiversity Loss (RBL); Reduce Carbon Emissions (RCE);

and Sustainable Futures (SF) (Table 1). BAU prioritizes exponential economic growth and debt-based CPO production over conservation, whereas RBL, RCE and SF prioritize biodiversity conservation, climate change mitigation and both of these, respectively 'Scenarios' section below). Finally, in this paper we refer to SES sustainability as a context where win-win-win results for the above-noted three indicators are achieved – where CPO production and biodiversity increase and CO_2 emissions diminish.

Scenario	Description
Business As Usual (BAU)	Rising global demand for vegetable oils drives oil palm plantation expansion in Indonesia, which consequently enhances increasing amounts of borrowed credits from overseas banks to finance CPO production. This process is financially beneficial for both banks and palm oil companies, yet it incurs biodiversity loss and global warming. The Government of Indonesia is more focused on creating jobs and reducing poverty through expanding the area of oil palm plantations. This situation is reinforced by weak environmental governance, as well as lack of funding allocated by international organizations for conservation.
Reduce Biodiversity Loss (RBL)	Funding for conservation (mainly international) increases, thus benefiting biodiversity by enlarging the protected area network and restoring moderately degraded forests in Indonesia. Furthermore, biodiversity loss is halted by firms using credits, as well as public funding, to cover the additional costs of creating new plantations in degraded lands and to increase production efficiency in existing plantations.
Reduce Carbon Emissions (RCE)	The government of Indonesia receives international funding to maximize above-ground biomass accumulation and reduce carbon emissions. Highly degraded forests are restored, due to their high potential to sequestrate carbon. The protected area network is enlarged, yet investments are lower than in RBL since area protection benefits biodiversity conservation more. Carbon sequestration is also enhanced by firms using credits and public funding to create plantations in degraded lands (with low carbon stocks) and increasing productivity in existing cultivations.
Sustainable Futures (SF)	Economically supported by international bodies and developed countries, the government's goal is to enhance win-win contexts regarding climate change mitigation and biodiversity conservation. Restoration of degraded land takes place in both highly and moderately degraded lands, which benefit biodiversity and carbon conservation. Furthermore, firms use credits and public funding to increase production efficiency in existing cultivations and create plantations in degraded lands.

Table 1: Narratives of the scenarios modelled.

2.2. Modelling framework

The ABM model was built using NetLogo (Wilensky, 1999). ABMs simulate systems of autonomous and heterogeneous agents; these interact with each other and the environment, making decisions and changing their actions and the environment as a result of these interactions (Ferber, 1999). Each agent is simulated using computer software as a data structure storing its attributes, together with algorithms that implement its behaviour, and an effect this has on other agents or the environment. ABMs are helpful for studying complex dynamics such as coupled human-natural systems (Balbi and Giupponi, 2010; Filatova *et al*., 2013), which are characterized by feedback loops, nonlinearity, thresholds, time lags, resilience, among other characteristics (An *et al*., 2014). ABMs have also proven useful in gaining general insights that support the sustainable management of resources through a better understanding of complex SES (Schulze *et al*., 2017). In particular, the benefits of using ABM for exploring complex coupled SES include: (i) the capturing of emergent phenomena; (ii) the simulation of heterogeneous agents, which allows the simulation of complex and nonlinear behaviours from different entities; (iii) modelling the social networks and physical space-based interactions; and (iv) obtaining a dynamic natural description of the SES studied, rather than only the final output results.

An increasing number of ABMs are being built within the land-use modelling community (Verburg, 2006). Since the earliest published Agent-Based Land-Use Model (ABLUM) (see Lansing and Kremer, 1993), models have gradually progressed from conceptual land-use frameworks (e.g. Epstein and Axtell, 1996) to more complex empirical representations of SES (e.g. Bousquet and Le Page, 2004). Recent reviews and examples of ABLUMs include Filatova *et al*. (2013), Matthews *et al*. (2007), Murray-Rust *et al*. (2013) or Polhill *et al*. (2011). Scholars have also studied the relationship between ABM and policy-making contexts. Gilbert et al. (2018) reflect on various experiences using agent-based modelling in policy-making contexts, noting that models can take on different roles when embedded in deliberations. They also observe that there are a number of realities of day-to-day policy-making that mean any modelling (agent-based or otherwise) can be difficult to incorporate successfully. Not least of these issues is that recommendations from model outcomes may be politically unacceptable. Summarizing the key lessons from the examples they describe, Gilbert et al. (2018, section 5) emphasize the issues agent-based modellers typically face with lacking data, but argue that this is not a reason not to model."

The methodological framework of this paper follows the TRACE documentation protocol (Grimm *et al*., 2011), a tool for planning, performing, and documenting good modelling practice. The following sections comprise short characterizations of the TRACE elements corresponding to 'Problem Formulation' – including a description of the study area and the scenarios modelled – 'Model Description' – using the Overview, Design concepts, and Details (ODD) protocol document (Grimm *et al*., 2006, 2010) – and 'Data Evaluation' – including model parameterization and calibration processes.

2.3. Model description

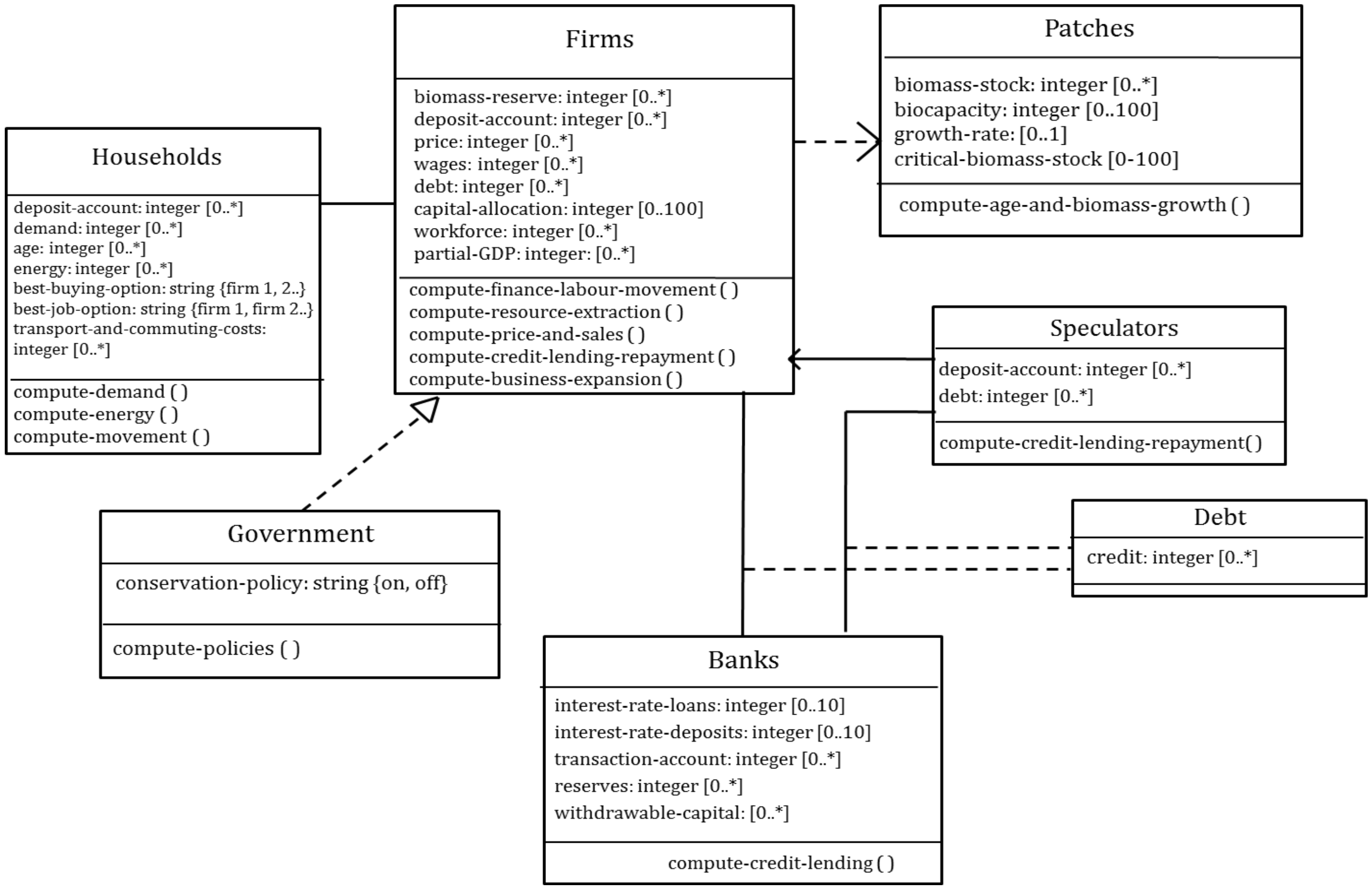
The model description follows the Overview, Design concepts, and Details (ODD) protocol document (Grimm *et al*., 2010). The following sections describe the 'Entities, state variables and scales' and 'Process overview and scheduling' elements from the ODD. Note that a description of the data used in the model is not provided in the main paper due to the length of the dataset. This and further empirical data about the model can be found in the Supporting Information (SI) document, where a full ODD version is presented. .

2.3.1. Entities, state variables and (spatio-temporal) scales

The key entities in the model are agents – representing firms, banks and the government – and the environment – consisting of a grid of land-covers (i.e. patches). The bank agent represents the overseas financial entities funding CPO production in Indonesia through bank credits, while firms represent the investment groups, i.e. forest-risk groups, financing CPO production in Indonesia. Finally, the government agent represents, as a whole, the national and international policies focused on protecting land and restoring degraded land in Indonesia. Note that that the latter is a conceptual type of agent, which does not compute any specific policy in particular; thus, it is used to represent the potential effects that both national and international policies (similar to REDD[1] schemes) would have on SES sustainability.

[1] REDD, which stands for Reducing Emissions from Deforestation and Forest Degradation, is a United Nations-led program offering incentives for developing countries to preserve and enhance forests.

The model includes a total number of 6,480 cells (i.e. land-covers), which include 14 secondary land-cover types; following Hill *et al*. (2015a), these are aggregated into three primary land-cover types, i.e. 'protected areas', 'semi-natural areas', and 'oil palm plantations'. Simultaneously, 'protected areas' and 'semi-natural areas' are categorized as 'non-forested' or 'forested', the latter being classified into 'lowland', 'montane', 'heath', 'peat swamp', and 'freshwater swamp'. Figure 2 shows a Unified Modelling Language (UML) class diagram describing the model entities and variables in detail. Furthermore, Table S1 (SI document) shows a description of the entities and state variables modelled, their units and data sources.



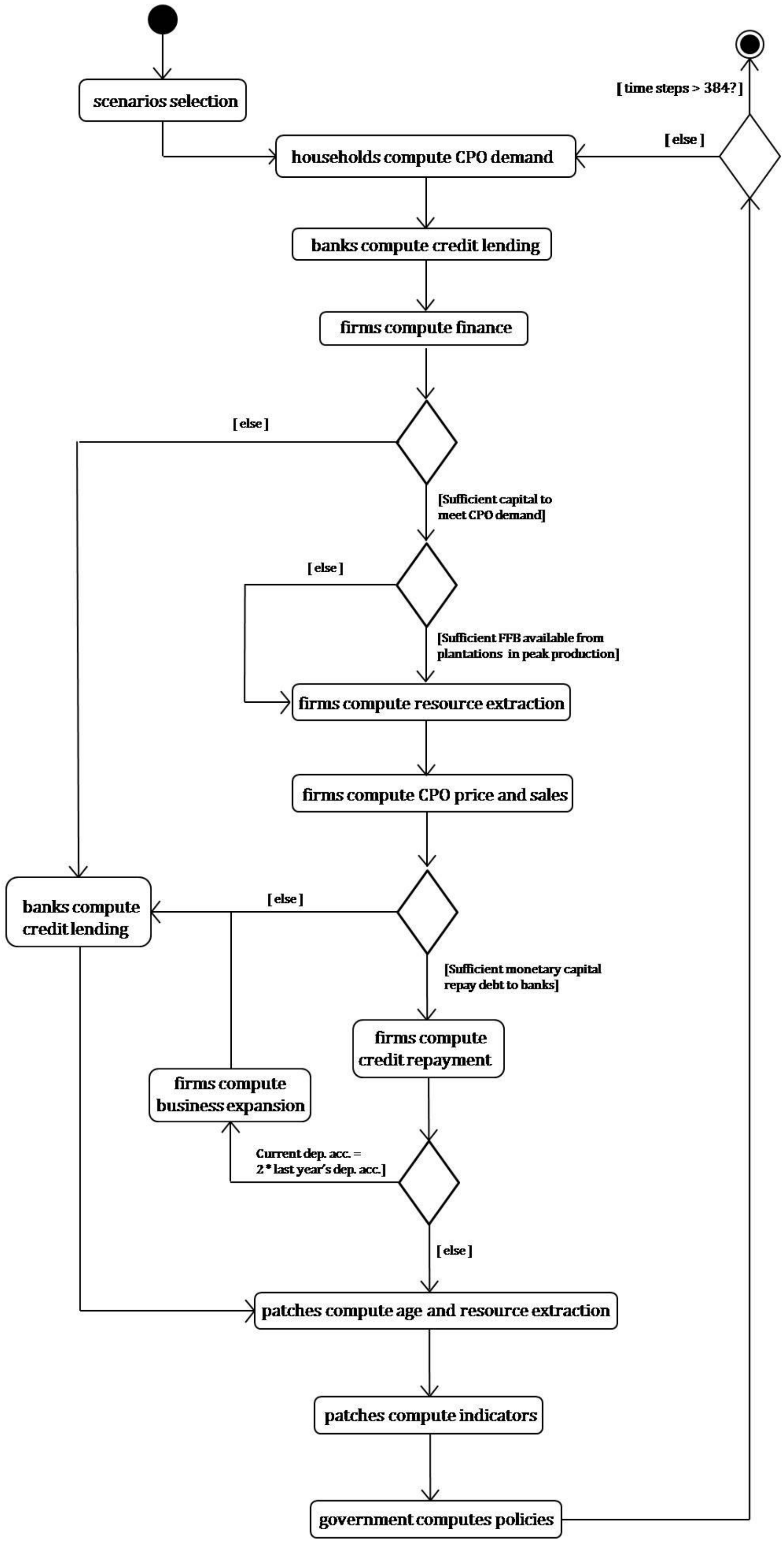
175 **Figure 2:** UML Class Diagram. Structure diagram showing the system's classes, their attributes, attribute values, functions/operations and relationship between classes.

The model comprises the period 2018-2050, where each time step corresponds to one month, thus running the model for 384 monthly time steps (i.e. 32 years). The period 2008-2016 is used for model parameterization and calibration (described below). The time-scale of the model was selected by comparing the modelling outcomes for CPO production and protected area expansion during the period 2008-2016 with historic data for these indicators during the same period. The reason for selecting these indicators to set the time-scale was because these drive the main land-cover changes and outcomes in the model. Thus, analyses of the calibrated results showed a qualitative alignment between both historic data and model outcomes when using a particular time-frame, based on 1 model time step corresponding to 1 month in the real world. The period to 2050 was selected to enable sufficient time for the outcomes of the various scenarios to be realized.

The spatial-scale of the model is considered to be sub-national/national, due to the case-study area comprising a relatively high (i.e. 80%) amount of the total land covered by Indonesia. Furthermore, the patch size selected (235.47ha) under this spatial-scale aligns with the previously selected time-scale (i.e. 1 model time step = 1 month). Oil palm expansion was responsible for an average of 270,000ha of forest conversion annually from 2000-2011 (Henders *et al*., 2015), making an average of 22,500ha deforested every month, i.e. every time step in the model. The patch size selected (235.47ha) is considered sufficiently large to enable the conversion, at the specific time scale selected, of similar amounts of land into oil palm plantations. The same case applies to protected area expansion and degraded land restoration processes. Therefore, the time-scale selected for the model is adjusted upon the spatial-scale, as the time needed in the model (under the selected time-frame) to compute land-use change aligns with the real-world land-use change processes in Indonesia.

2.3.2. Simulation process and overview

Figure 2 shows a UML activity diagram representing the dynamics of the system and the flow from one process to the next. The following is the list of model processes taking place every time step, which are described in detail below (see the SI document for a detailed description of model functions and algorithms): (i) compute CPO demand; (ii) banks compute credit lending; (iii) firms compute finance; (iv) banks compute credit lending; (v) firms compute resource extraction; (v) firms compute CPO price and sales; (vi) firms compute credit repayment; (vii) firms compute business expansion; (viii) patches compute age and resource extraction; (ix) patches compute indicators; (x) government computes policies.



211 **Figure 3**: **UML Activity Diagram**. Structure diagram showing the step by step process computed by
212 agents and patches in the model.

The SES modelled is simulated under a debt-based economy, where each scenario (see Table 1) sets different rules and limits affecting the dynamics and relationships between agents and the environment. First, CPO demand (exogenously computed) is computed on a monthly basis and distributed among the existing firms based on their current price (explained below); note that CPO demand represents the consumption by households (consumers), which are not agents in the model. Second, firms borrow credits from the bank upfront, i.e. at the beginning of each financial year, in order to cover the direct and indirect operating costs of CPO production in current plantations, including resource extraction, wages for employees and other daily expenditures. Third, firms calculate the final monetary capital needed to cover the expenses for the following month using information on CPO demand; therefore, further credits are borrowed if additional funding to meet the CPO demand is needed.

Firms harvest fresh fruit bunches (FFB) from the plantations they own, which is the fruit produced by oil palm trees from which CPO is obtained. Firms prioritize those plantations where the average tree age ranges between 7 and 18 years – peak production of oil palm trees –since yield gradually decreases after 18 years (Wilmar, 2017). Oil palms begin to produce fruits 30 months after being planted, with commercial harvest commencing six months later. Oil palm plantations with trees older than 25 years – max commercial lifespan – are cut down by the firm owning that land, and are replaced by new plantations with a starting age of 0 from the following month onwards. If firms cannot meet the monthly CPO demand by solely harvesting FFB from peak production plantations, those plantations with trees older than 18 years are harvested until demand is met, followed by those from 3-7 years.

After finishing the monthly harvesting process, each firm sets a price based on a combination of historic information, predicted data and other firms' prices. The firm offering the lowest price is placed at the top of a right-skewed distribution (showing price on the x-axis and demand in the y-axis), thereby being the one prioritized by consumers. When the total CPO demand for that month is met, the CPO selling process stops.

At this point, firms must start paying back their credits, with interest, to the bank. Note that, although firms in the model borrow/repay credits from/to one single bank, this bank agent (the only bank agent in the simulation) represents all financial entities, from overseas, lending money to oil palm companies in Indonesia. Furthermore, the model does not consider variations of the interest rate, despite this is known to be a major risk of debt-based agricultural production. This is because the economic system modelled does not take into account those international economic factors and processes that normally influence interest-rate variations. Hence, the model does not create endogenous interest-rate variations by itself. Nevertheless, including parameters into the model to exogenously enhance interest variations instead would not ensure the aligning of model interest oscillations with the real-world ones. Therefore, the model just integrates the constant interest-rate value provided by the World Bank in 2016. Furthermore, note that firms continuously borrow credits to cover their direct and indirect operating costs regardless of the interest to be paid.

If firms have sufficient monetary capital in their deposit accounts, firms compute the credit repayment corresponding to that month; otherwise firms borrow a credit to cover the debt. Firms also consider expanding their business if their income shows a positive net increase compared to historic data, and their expectations about future profits are positive. In such case, firms borrow a bank credit. The identification of potentially suitable sites for new plantations follows Gingold *et al*. (2012) and is a scenario-dependent decision – where firms select areas based on their (CPO) production potential, land-cover availability and conservation potential. Eventually, each firm's monthly income varies depending upon the profits obtained from CPO sales, and the expenditure on the wages allocated to employees, resource extraction processes (i.e. materials and equipment, plantation maintenance), technological investments to improve CPO production efficiency, and debt repaid to the bank. While costs associated with debt, wages, resource extraction, material and equipment are mandatory monthly expenditures, firms' investment in technological development is a scenario-dependent decision.

Each oil palm plantation land-cover computes an age function, as well as a stock and a growth function regarding FFB. Furthermore, each land-cover (patch) computes biodiversity and carbon stock algorithms, which change over time, based on the type of land-cover change taking place in that patch and the surrounding matrix of patches. Furthermore, while the biodiversity function considers the previous, current and next land-cover changes – both in each land cover and the surrounding ones –, carbon is calculated from losses/gains in above-ground biomass (AGB), which is then converted to carbon and CO_2. Based on the amount of AGB, each land-cover computes a degradation grade that is used for restoration purposes (see below).

The government (representing national and international public institutions investing in conservation in Indonesia) may intervene in the simulation by increasing government expenditure (GB) leading to strong (scenario-dependent) government policies. These interventions affect firms' decision-making and land cover variables, thus influencing model outcomes. More specifically, GB is focused on implementing conservation policies through allocating public funding to firms, i.e. similar to Payments for Ecosystem Services (PES) (Farley and Costanza, 2010; Wunder, 2008), in order to encourage firms to cover the additional costs regarding the following actions: (i) increasing CPO production efficiency on existing plantations by investing in technological development, and (ii) creating new oil palm plantations solely on degraded lands, instead of areas with high biodiversity and carbon stocks – which are, in principle, more profitable. Furthermore, governments can also invest in (iii) degraded land restoration, and (iv) protected areas. The selection of those land-covers to be restored and protected is based on the grade of degradation and the conservation potential, respectively, while the financial opportunity cost of CPO production is calculated (at the national level) based on the revenue foregone from CPO production as a consequence of restoration and protected area creation. As previously mentioned, the government agent, which implements the above-noted four (i-iv) GB-driven processes, represents mainly international bodies and agreements (such as REDD programs), since such conservation investments and policies are unlikely to be (solely) performed by the Government of Indonesia.

2.4. Scenarios, data evaluation and run setup summary

Table 1 shows a qualitative description of the rationale for each scenario (i.e. BAU, RBL, RCE and SF), while Table S5 (SI document) describes the parameters, target values and data sources selected to build and compute each scenario. Note that expert opinion was used to set the rationale for each scenario and to determine the parameters selected for the different scenarios.

We follow the TRACE documentation (Grimm et al., 2011) to perform both model parameterization and calibration processes. Model parameterization focuses on exploring model parameter values, including a list of all the parameters and values, the data sources, and how the parameter values were obtained (Railsback and Grimm, 2011). In addition to Table S5 for scenarios, Table S1 (SI document) shows the model entities and their state variables, as well as the parameter types, their values/units and data sources. Among the data sources and historic data integrated in the model, of note is the use of historic banking data on debt, which drives bank and firm agents' decision-making processes. This dataset, obtained from the dataset Forest and Finance (2016), shows up-to-date information regarding the amount of credits lent by international banks to different industrial sectors in Southeast Asia, focused on funding the production of different goods and services, e.g. palm oil, timber, cotton. The dataset includes the name of banks (lenders), types of industries (borrowers), name of firms, type of credit facilities, amount allocated per year, among other information. Other empirical data integrated in the model includes the area covered by each land cover, oil palm trees' growth rate, CPO prices, and carbon sequestration rates, among others (see Table S1, SI document).

For the purpose of model calibration, both historic and literature data sources for the period 2008-2016 were used. The full model calibration process, including calibration results, is described in detail in the SI document.

Finally, the model results were obtained by computing each scenario 150 times – considered a reasonable number of runs in simulation models (see Ritter et al., 2011) – making a total of 600 runs. Each simulation was then run for 384 time steps (32 years, 2018-2050), where the average and standard error values from all the runs for each simulation are shown in the result figures.

3. Results

The results obtained are shown in Figures 4, 5 and 6. These were qualitatively analysed with the objective of comparing, and identifying, differences in trends among the indicators selected – within and between the scenarios modelled.

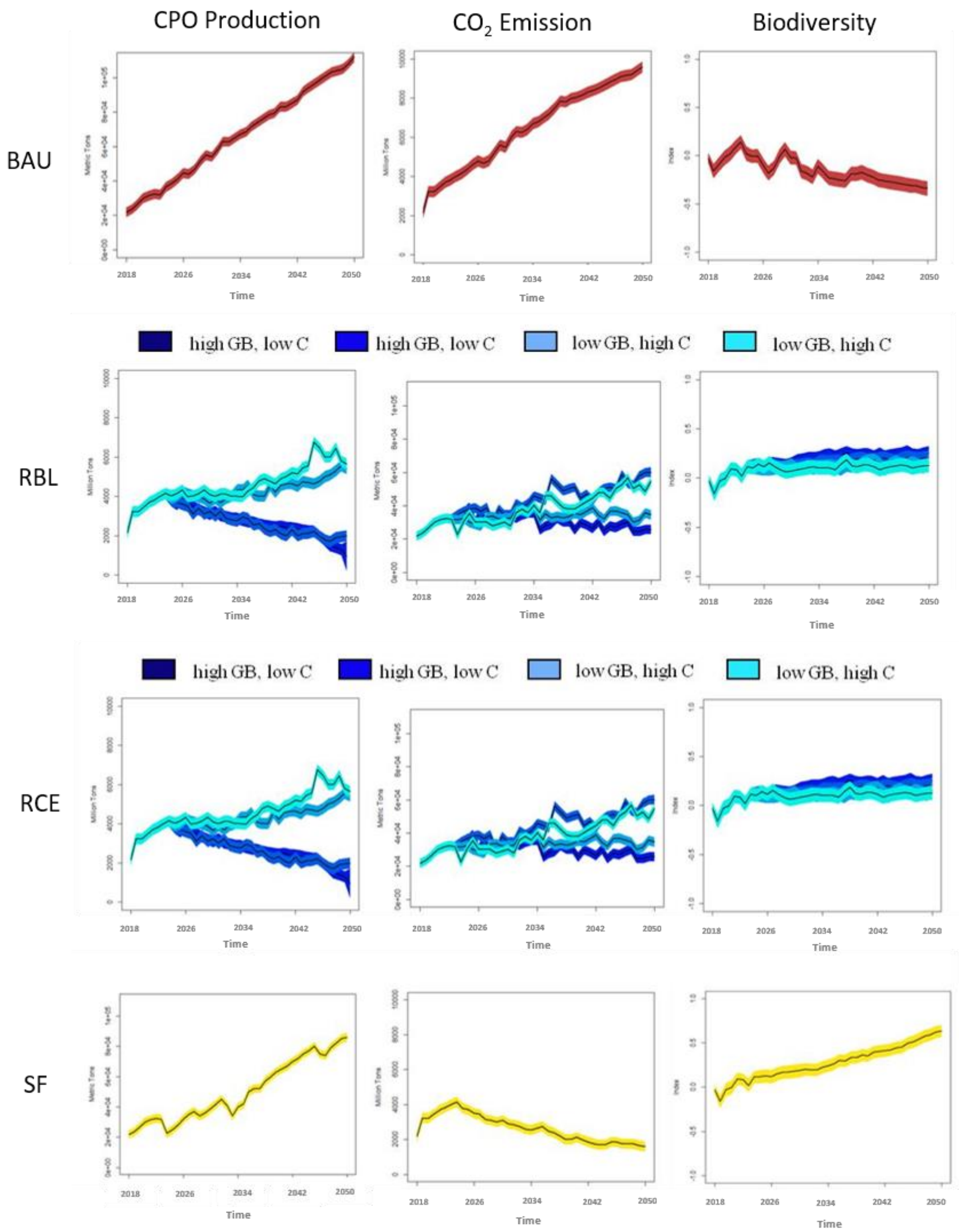


Figure 4: **Results for SES sustainability indicators**. Indicators include: crude palm oil (CPO) production (metric tons); CO_2 emissions (metric tons); and biodiversity (index) – where plots show the individual net values per year. Results obtained under projected future scenarios (BAU = Business As Usual; RBL = Reduce Biodiversity Loss; RCE = Reduce Carbon Emissions; SF = Sustainable Futures). Coloured bands represent the standard error bars including all the runs computed for each indicator under every scenario, while black lines show the mean values. RBL and RCE scenarios are divided in four sub-scenarios each: the darker the band's color, the stronger the conservation forces and the weaker the economic forces (i.e. high government expenditure (GB) for conservation, low availability of bank credits (C) for production). In contrast, light colored banks refer to strong economic and weak conservation forces.

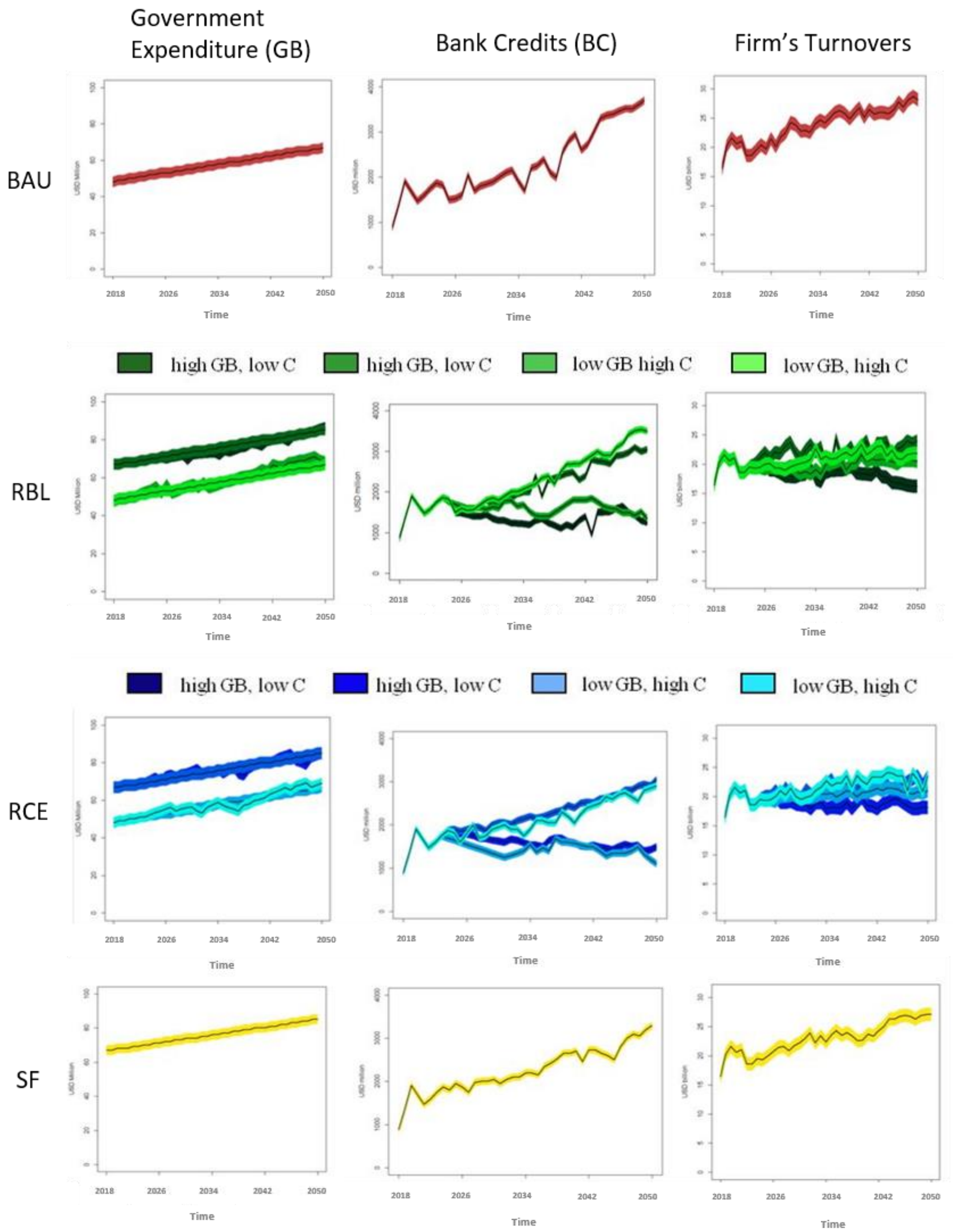


Figure 5: **Results for economic indicators**. Indicators include: Government Budget (USD million); Bank credits (USD million); and Firms' turnovers (USD billion), under each scenario.

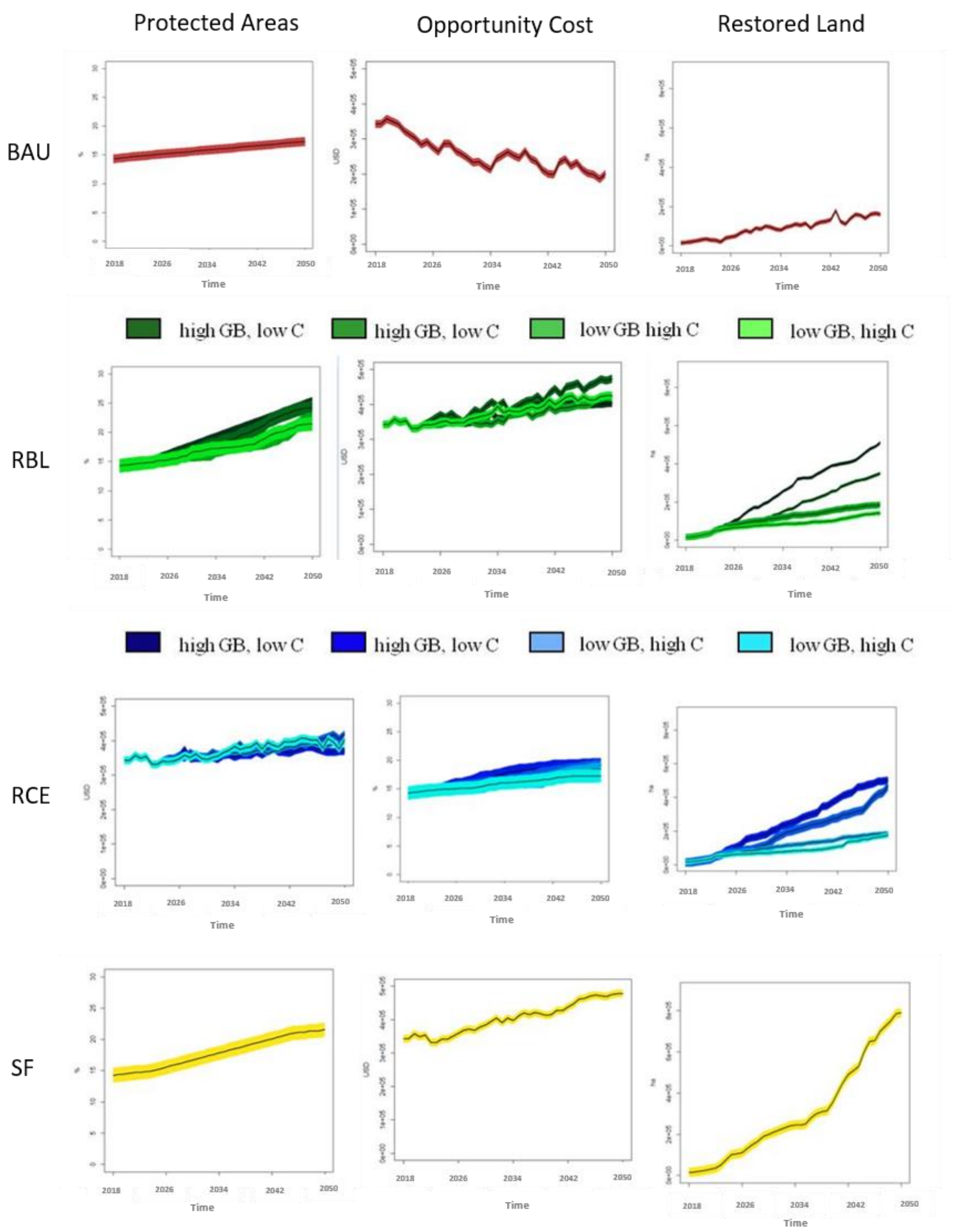


Figure 6: **Results for land cover change indicators**. Indicators include: protected areas (percent values); restored land (ha); and opportunity cost (in USD) for the oil palm industry of increasing protected areas and restoring land, under each scenario.

3.1. Business As Usual (BAU)

The first row in Figures 4, 5 and 6 shows the results obtained under BAU. This scenario shows the highest values for most economic indicators, while environmental outcomes show mainly negative trends. This is due to the protection forces in Indonesia not being sufficiently strong to halt the economic forces driving land clearing for CPO production. Thus, oil palm firms require a continuous flow of bank credits to expand oil palm plantations – normally into areas with high biodiversity (e.g. undisturbed upland forests) and high carbon stocks (e.g. swamp forests). As a result, the number of credits borrowed and CPO production increase over time, while the opportunity cost of not converting land into oil palm plantations continues to decrease. Concurrently, biodiversity loss and CO_2 emissions are reinforced, also due to the low level of government policies to support conservation – which nevertheless are steadily increasing over time. Regardless of the weak protection forces compared to economic ones, protected and restored land slowly increase, which aligns with current data regarding terrestrial protected land (World Bank, 2018).

3.2. Reducing Biodiversity Loss (RBL) and Reducing Carbon Emissions (RCE)

The second and third rows in Figures 4, 5 and 6 show the results obtained for RBL and RCE scenarios, respectively. As previously indicated, each RBL and RCE scenario is divided in four different sub-scenarios, with varying values regarding two variables: BC (bank credits) and GB (government budget); in particular, four different sub-scenarios are considered, namely high GB and low BC, high GB and BC, low GB and BC, and low GB and high BC. These refer to the amount of monetary capital initially (i.e. at the beginning of the simulation) available for conservation and CPO production, respectively. Furthermore, GB and BC are invested in different conservation and production strategies characteristic of each scenario

RBL and RCE scenarios show similar trends for most indicators, which, as per the SF scenario (see below), minimize land requirements by intensifying CPO production. Some monetary-economic indicators (credits borrowed by firms and firms' turnovers), as well as some environmental indicators (CPO production), show more negative results than those under BAU, due to economic forces driving land clearing for CPO production being weaker than conservation forces. Under RBL, strict enforcement of forest protection enhances the creation of new protected areas, land restoration and the creation of new policies that force firms to decrease the number of new plantations in areas with high biodiversity. Biodiversity, therefore, increases with higher GB values; the same occurs for CO_2 emissions, where more sustainable results are obtained under scenarios with high GB values. The main difference between RBL and RCE, in terms of biodiversity and CO_2 emissions, is based on the type of forests restored: while moderately degraded forest is least favoured for restoration under RCE, highly degraded forest is least favoured under RBL, thus enhancing higher biodiversity values under RBL and lower CO_2 emissions under RCE (see Table 1).

3.3. Reducing Biodiversity Loss (RBL) and Reducing Carbon Emissions (RCE)

The fourth row in Figures 4, 5 and 6 shows the results obtained under the SF scenario. This is the only scenario showing synergies between CPO production, CO_2 emissions and biodiversity, as well as relatively positive results for the rest of indicators. As analysed in the Discussion section below, these results reflect a combination of the following factors: (i) the use of technology by firms to increase production efficiency in existing cultivations, which significantly reduces land requirements for CPO production; (ii) the creation of new plantations solely on degraded lands, thus avoiding plantation expansion into areas with high biodiversity and carbon stocks; (iii) the increase in the amount of degraded land restored; and (iv) the increase in the number and extent of protected areas.

3.4. Environmental impacts of Power Imbalances between banks and government RCE)

Results shown in Figure 7 allow us to explore the extent to which biodiversity and CO_2 emission values vary under different Power Imbalance contexts between economic forces (represented by banks and credit allocation to firms, i.e. BC) and conservation forces (represented by the policies and budget allocated for conservation, from both national and international public entities, i.e. GB), under each scenario. The calculation of Power Imbalance values (i.e. *x-axis*) follows a simple calculation process between BC and GB – see SI document for more information.

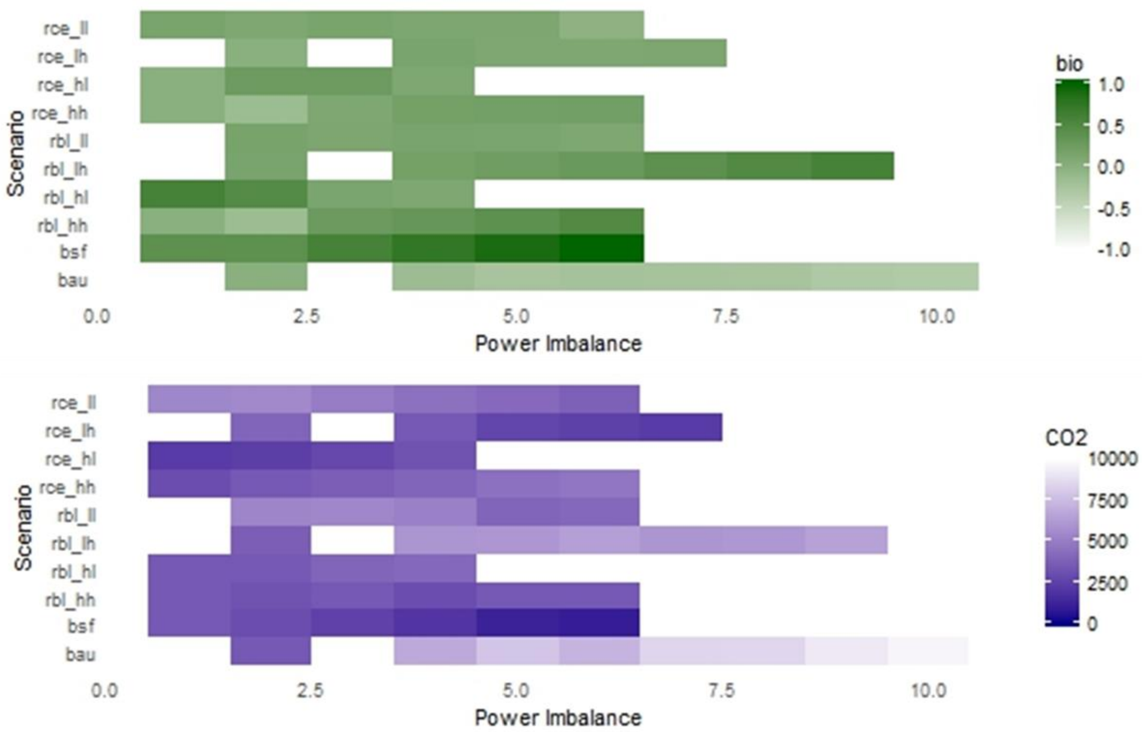


Figure 7: **Impact on biodiversity and CO_2 emissions of Power Imbalance values**. The top heatmap shows the impact of different power (im)balance rates between economic and conservation forces on biodiversity, while the bottom heatmap shows the same impacts on CO_2 emissions (in millions of tons). Dark coloured cells represent high values, while low values are represented by light coloured cells. Cells in blank show those scenarios with neither biodiversity nor CO_2 emission values computed for certain Power Imbalance values. See main text for an explanation of the abbreviations in the y-axis.

The higher the power imbalance values (i.e. right-hand side values in the *x-axis*), the higher the amount of BC available for CPO production compared to GB for conservation. The lower the power imbalance values (i.e. left-hand side values in the *y-axis*), the lower the amount of BC available for CPO production compared to BC.

Both RBL and RCE scenarios are divided in 4 different sub-scenarios each, showing the amount of monetary capital initially available for CPO production (BC) and conservation (GB). The following list disaggregates the abbreviations shown in the *y-axis* for RCE and RBL scenarios, where ‘h’ refers to ‘high’ and ‘l’ to ‘low’. See Table S5 (SI document) for the values referring to high and low:

- RBL_ll: RBL scenario with low (‘l’) GB and low (‘l’) BC.

- RBL _lh: RBL scenario with low ('l') GB and high ('h') BC.
- RBL _hl: RBL scenario with high ('h') GB and low ('l') BC.
- RBL _hh: RBL scenario with high ('h') GB and high ('h') BC.

Note that each scenario (*y-axis*) not only consists of different GB and BC values (i.e. monetary capital invested for conservation or CPO production), but also includes other processes and properties characteristic of each scenario, e.g. different rates of technological efficiency selected for CPO production by firms, potential areas selected for restoring degraded lands (see Table S5, SI document).

Figure 7 shows that high Power Imbalance values (i.e. *x-axis*), under the BAU scenario (i.e. *y-axis*), exert negative impacts on both biodiversity and CO_2 emissions. In contrast, the SF scenario shows considerably higher values for both indicators. The different sub-scenarios represented by RBL and RCE show varying results regarding both indicators, including trade-offs among sub-scenarios, with predominantly better results (in terms of sustainability) obtained for biodiversity under RBL and CO_2 under RCE.

4. Discussion

4.1. Analysing the relationship between conservation forces, economic powers and SES sustainability in Indonesia

Oil palm development, forest conservation and climate change mitigation are strategies that are, at first glance, in opposition to one another (UNEP, 2011). Considering that the same debt-based economy is modelled under both BAU and SF scenarios, the main factor driving SES (un)sustainability among these scenarios is the (in)appropriate use that oil palm companies make of bank credits – rather than the amount of credits borrowed or the debt-based nature of the economic system itself. Thus, the problem causing unsustainable outcomes is not the economic system itself – an economic system that creates a high dependency of different actors on debt and banks – but the purpose for which credit facilities are borrowed and allocated. In fact, the SF scenario (Figure 7) shows synergies between debt (i.e. credits borrowed), high biodiversity and low CO_2 emissions, showing that the use of bank credits more in line with concerted land conservation may be beneficial for SES sustainability. These results, therefore, align with recent research arguing that the current utilization of credit facilities by firms – focused on covering daily operating costs and expanding oil palm plantations into areas with high biodiversity and carbon stocks – is a key problem for sustainability in Indonesia (Alwarritzi *et al*., 2015). In this regard, scholars argue that using bank credits to increase production efficiency in existing oil palm cultivations could be sufficient to meet the growing world demand for Indonesian CPO, while helping conserve the highly valuable habitats in terms of biodiversity and carbon sequestration. For instance, Fairhurst (2009) shows that yield improvements in existing cultivation alone could potentially avoid the need to expand into 1.6 million hectares of forest. Simultaneously, planting oil palms in degraded land is suggested as an alternative solution to help meet global CPO demand, while avoiding the release of excessive CO_2 to the atmosphere and further biodiversity loss (Koh and Ghazoul, 2010).

The problem with alternative solutions focused on enhancing sustainable CPO production is that debt-dependent palm oil companies, such as firms under the BAU scenario, are unlikely to use credit facilities to finance less profitable, financially riskier 'innovative' CPO production processes, i.e. create new plantations in degraded lands and investing in technological efficiency (e.g. high-yielding oil palm genome projects, or information systems providing real-time results on palm oil plantations). Similarly, banks are unlikely to lend to firms unless the credit is used to finance processes or activities that ensure short-term profits for firms and, thus, provide financial security for banks. Currently, traditional oil palm cultivation, in biologically rich areas, provides firms with higher short-term profits, due to the low price of land in these areas. In fact, ‘innovative’ palm oil companies (i.e. firms implementing the above-noted more sustainable strategies) would probably be under-cut on international markets by traditional palm oil producers from other countries (i.e. BAU firms). In view of this, there is a need to financially support oil palm companies to shift their BAU paradigm to more sustainable scenarios. For instance, our model shows funding being allocated to oil palm companies under the SF scenario, which helps firms cover the additional costs of increasing technological efficiency in existing plantations and establish new plantations in degraded lands. Thus, new financial mechanisms could help firms cover the currently higher costs of adopting more sustainable practices (see Ruysschaert *et al*., 2011); until technological development or the market itself – due to land scarcity – starts inherently supporting more sustainable CPO production, i.e. due to a reduction of prices and operational costs related to more sustainable practices.

In this regard, PES (Farley and Costanza, 2010; Wunder, 2008) could be considered a potential short-term (temporary) solution within the transition towards long-term sustainability. PES seek to ascribe monetary value to ES (Bellver-Domingo *et al*., 2016), for instance through international schemes, such as REDD programs. REDD offers incentives for developing countries to preserve and enhance forests, thus offsetting the growth in global GHG emissions (Angelsen, 2008). The model presented here shows that, if sufficient funding is allocated to firms for enhancing more sustainable CPO production mechanisms, short- and medium-term synergies among the sustainability indicators explored could be reinforced. In fact, results show that this could take place without having to replace the debt-based (economic) production system nor reducing the current power of banks. Thus, there is a need to increase the socio-political and financial support from international bodies to Indonesian oil palm companies (e.g. PES schemes) to enhance the delivery of multiple beneficial ES. As an example, as a follow up of the United Nations Climate Change Conference held in Cancun, Mexico, Indonesia signed a US$1 billion deal with Norway in 2010, under the REDD framework, aimed at reducing deforestation (Lang, 2010). Furthermore, it is expected that 200 billion Euros will be transferred world-wide through PES schemes by 2020 (GIZ, 2016). The problem here is that funding for development is usually much higher than that for conservation (Hill, 2015b; Laurance 2018); for instance, the leaders of the G20 nations gave a huge boost to the power of development regimes by promising to invest 60-70 trillion U.S. dollars for new infrastructure projects by the year 2030 (Hill, 2015b; Laurance, 2018). Therefore, if the objective is for PES to be able to compete with the agricultural sector, investments for PES and other financial mechanisms need to increase (Butler *et al*., 2009).

Besides this, results obtained under low Power Imbalance values in the SF scenario (see darker coloured cells under RBL_hl and RCE_hl scenarios, Figure 7) also show the need to enhance conservation forces in terms of increasing the number and extent of protected areas, as well as restoring degraded land. Under these scenarios, the power of governance forces driving land protection and restoration is higher than that from banks and economic forces driving land clearing for CPO production. As a result, Figure 7 shows the positive impact in biodiversity and carbon sequestration of having stronger conservation forces. Furthermore, an increase in the funding allocated for both enlarging the current protected area network and restoring part of the 46.7 million hectares of degraded land present in Indonesia would help drive sustainability. These results can help the Indonesian government in responding to recent criticism (Murdiyarso *et al*., 2011) about giving greater importance to land protection than restoration through the REDD agreement with Norway. In fact, recent research demonstrates that the creation of protected areas in Indonesian forests is a less effective way of halting deforestation and biodiversity loss than restoring degraded land (Symes *et al*., 2015). Yet, our results demonstrate the two pathways are not mutually exclusive and support both ongoing protected area creation and the proposal for the inclusion of part of the 400,000 hectares of highly degraded lowland forest into the moratorium.

It is important to note that the outcomes of the model are dependent on the framing of the scenarios and the model itself. In this regard, though it makes policy recommendations, the work discussed here is not embedded in a policy-making process, but instead uses a case-study to explore the principles underlying the role of debt in managing SES. As Polhill et al. (2019) note, policy-makers typically rely on a diverse, trusted sources when making decisions, and, critically, the results from the model need to be delivered in a clear, transparent way at the right time. The point is picked up by Elsawah et al. (2020), who, discussing models of SES in general (not just ABMs), suggest improving modellers' understanding of the processes underlying political decision-making as a way forward. Haigh's (1998) observations on the development of European policy on lead in petrol is an instructive, if little-cited, starting point in that regard.

Overall, our results, from our SF scenario, show evidence that, with various adjustments, a compromise solution regarding the dual objectives of CO_2 emissions and biodiversity – while enhancing CPO production and oil palm companies' income – can be achieved under a debt-based economy. More specifically, these mutual benefits occur when firms make a more appropriate, and sustainable, use of credit facilities, and when governments support stronger conservation policy in Indonesia. In this regard, the role of international financial support will be essential to compensate the lack of incentives allocated by the Indonesian Government for environmental conservation. The latter situation is reinforced by governments from developing countries being usually more focused on reducing poverty and social issues than on solving environmental sustainability issues (Redfield, 1996).

Yet, whilst our model shows evidence that, under certain conditions, achieving a win-win-win outcome in Indonesia is potentially achievable, we argue that it is necessary to perform sustainability studies that go beyond trade-off analyses. Examining the nature, and inherent mechanisms, of debt-based SES can help us to explore whether these can be truly sustainable in the long-term. The following section explores this issue as a starting point regarding the internal and external mechanisms that may be driving long-term (un)sustainability in Indonesia.

4.2. What factors enhance system rigidity and long-term (un)sustainability in debt-based SES?

Besides achieving win-win-win scenarios for the selected indicators (i.e. SES sustainability in this paper), long-term sustainability can be defined as a system's ability to persist over time (Dawson *et al.*, 2010). In other words, sustainability occurs over an infinite time horizon in which the objective is to maintain system functions, i.e. the goal is to continue to play the game (Carse, 1987). Although our modelling shows positive results for different indicators, some scholars argue that Indonesia possesses some particular characteristics that could be hindering long-term sustainability (Ulanowicz *et al*., 2009). Besides the trade-off analysis performed, our results also show the lack of capacity of the SES modelled to cultivate internal autocatalysis, as well as its high dependency on unstable external financial institutions. It is argued that these characteristics turn SESs into ‘rigid’ systems (see Burkhard *et al*., 2011). System rigidity refers to a situation where a system becomes so efficient in its processes that there is little room for further innovation and sustainability (Fath *et al*., 2015). Characteristics of a rigid system include: very few key nodes and a high concentration of influence; being highly vulnerable to external disturbances because of reduced diversity (Fath *et al*., 2015); and brittleness, i.e. lack of resilience (Jackson, 2010). As shown by our model, Indonesia possesses a high dependency on external financial institutions (i.e. banks), with two main nodes (i.e. palm oil industry and banks) and a primary single pathway connecting both agents, “navigated” by credits and interest.

We highlight four main socio-economic and political factors that could be strengthening, and reinforcing, long-term system rigidity in Indonesia. First, Indonesia is the top exporter of palm oil in the world; between 2000 and 2014, exports and consumption of CPO in Indonesia increased from 5 to 22Mt and from 3 to 11 Mt, respectively (USDA, 2014). The current significant contribution of oil palm production to regional, national and local economies (Zen *et al*., 2005) will be supported, at least in the near future, by doubling the land area under oil palm by 2020 (UNDP, 2015). Second, CPO production has resulted in economic improvement of rural areas by providing jobs for local people (Hirawan, 2011). More specifically, increasing agricultural incomes from CPO production is critical for poor smallholder households that depend largely on natural resources for their livelihood (Klasen *et al*., 2013). Third, system rigidity is also enhanced by the reliance of the palm oil industry on upfront capital funding from overseas banks, needed to develop land, plant seedlings and build infrastructure (Chain Reaction Research, 2017). Thus, the current debt-based palm oil industry is supported by both banks and the industry itself, since it enhances a win-win economic context where the former gain benefits from the interest on their loans and the latter continues to increase its turnover due to the rising demand for CPO. Moreover, the risk averse nature of banks and farmers, as well as the high operational costs, leaves little room for change in terms of carrying out more sustainable practices (Ruysschaert *et al*., 2011). Last, but not least, weak conservation governance in most tropical countries does not help to counterbalance system rigidity supported by the debt-driven palm oil industry. This places BAU economic forces at a privileged position at the expense of conservation forces (Hill *et al*., 2015a). As a result, developing countries, such as Indonesia, do not possess enough funding for conservation (or are not willing to use it for that purpose), nor receive enough international financial support. For instance, although Indonesia signed the US$1 billion deal with Norway under the REDD framework (Lang, 2010), so far, the agreement has not made much difference to the rate of deforestation – due to corruption, bad practices, and stronger economic forces compared to conservation (Lang, 2010; Lang, 2017).

With regard to the win-win context created by the debt-based CPO production for both the industry and banks, it important to mention that 14 of the 32 Indonesian billionaires identified by Forbes magazine have accumulated their wealth at least in part through the palm oil industry (Forbes, 2018). This includes 6 of the country’s 10 richest, and 12 of its wealthiest twenty. Since Indonesia continues to be the world's top producer of the commodity since the palm oil boom of the 2000s, this country is becoming one of the most unequal societies. Hence, wealth is concentrated in few billionaires while the rest of the country remains poor at lower socio-economic scales.

The previously mentioned factors are creating a 'rigid' context in Indonesia; where a debt-driven CPO production system, in which the debt is not used in ways that promote sustainable outcomes, will likely continue to be socio-economically supported in the long-term by different key actors – including banks, oil palm companies, farmers and the government. Thus, a long-term shift in the mainstream BAU thinking is required among palm oil stakeholders and farmers through novel farmer policy guidance, environmental legislation and incentive mechanisms to drive sustainability. In this regard, in addition to the previously discussed PES schemes, favouring partial public (governmental) intervention in the CPO market system could also help reducing system rigidity. For instance, market intervention through different policies could address the Indonesian smallholders' aversion to risk, currently represented by their unwillingness to use credit facility to create new plantations in degraded lands. Hence, cheaper bank financing mechanisms (e.g. interest-free loans) offered by more secure financial entities, e.g. micro-finance institutions (see Ruysschaert *et al*., 2011) could incentivize a more sustainable use of bank credits by farmers. Similarly, stronger conservation governance could help compensate for the negative environmental impacts exerted by the stronger financial powers driving land clearing in Indonesia. In fact, good conservation governance has proved successful in reducing deforestation and the number of unprotected forests in some tropical areas, such as the Amazon (Soares-Filho *et al*., 2006). However, high levels of corruption and low public governance quality in

Indonesia, which was ranked second to last in a Global Competitiveness Report survey in 2015 (OECD, 2016), could be hindering long-term sustainability and system rigidity through low levels of funding allocation for environmental conservation (Sodhi *et al*., 2007). We argue that the problem here is the political difficulty of implementing policies that, indirectly, reduce the power of influential financial institutions that are not interested in any paradigm shift. Thus, governments are usually not free to create new institutions that could help encourage long-term sustainability, but must take account of the influence of industries and other interest groups (Abel *et al*., 2006). This is due to the high dependency of national economies on very few corporations or monopolies, which could be one of the reasons why systems so often remain maladapted to current unsustainable conditions, to the point of collapse (Abel *et al*., 2006).

We argue that developing countries, such as Indonesia, could benefit from better conservation governance, as well as higher levels of public expenditure through international PES schemes (Hopkin and Rodriguez-Pose, 2007). For this purpose, governments from developed countries will need to assist developing countries in their effort to enhance natural resource sustainability under debt-based economic systems (Balmford *et al*., 2002).

5. Conclusions and further research

The results of our modelling of the debt-based CPO in Indonesia shows that achieving sustainability is largely depending on whether the Indonesian, and global, societies are prepared to either pay the financial and societal costs of reigning in oil palm development, or accepting a comparatively smaller trade-off with agricultural land in return for increasing environmental sustainability. We show that it is possible to pursue a course of sustainable development that substantially minimizes trade-offs in the short to medium-term. In particular, the modelling (SF scenario) showed synergies among different sustainability indicators under certain socio-economic and governance contexts. The alternatives – whereby economic growth has priority through oil palm expansion (BAU scenario), or biodiversity and CO_2 absorption are indirectly enhanced together with a partial decrease in CPO production (RBE and RCE scenarios) – implied substantial losses of either biodiversity or CPO stocks (or both), with increasing CO_2 emissions.

More specifically, we conclude that:

(1) *economic-development forces are stronger than conservation forces in Indonesia*, driven by an inappropriate, and unsustainable, use of credit facilities by palm oil companies. This situation is currently strengthened and reinforced by weak conservation governance;

(2) *synergies among ES and biodiversity can be enhanced; not by incurring a change or replacement of the current debt-based economic or CPO production systems, but by shifting the mainstream BAU thinking of key economic actors*. Shifting market-driven, capitalist forces to support environmental conservation requires novel farmer policy guidance, environmental legislation and incentive mechanisms from international bodies and developed countries; and

(3) *there is a need to enhance conservation governance in Indonesia.* Not only in terms of increasing protected areas and restoring degraded land, but also favouring partial, responsible governmental intervention in the CPO market system.

This research, and its conclusions, could be strengthened by modelling a more complex banking system, including further credit lending mechanisms; and exploring the extent to which overseas banks are willing to lend credits to firms to finance innovative CPO production processes (e.g. for technology efficiency improvements and degraded land upgrading) – instead of traditional palm oil cultivation processes. Exploring alternative banking mechanisms that enhance profits for both firms and banks, while supporting environmental conservation, would strengthen the analysis. Conservation forces can be further specified in the model by integrating specific empirical data from current PES schemes. Furthermore, the model could benefit from carrying out participatory processes with stakeholders, including farmers and government agents, banks and oil palm companies. Thus, integrating data from the bottom-up would enable a more detailed modelling analysis regarding the relationships, adaptive behaviour and dynamics between agents and the environment modelled, and provide opportunities for them to learn from one another in ways that could drive greater support for sustainability initiatives that produce win-win-win outcomes.

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